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A Networking Protocol for Underwater Acoustic Networks

1 Motivation

There exists an increasing demand for reliable, high capacity Underwater Acoustic Networks (UANs), as evidenced by the large volume of research invested over the last decade in overcoming the difficulties inherent with propagation of information bearing signals through shallow water regions. Application interests include oceanographic information gathering, environmental monitoring, and coastal defense (anti-submarine and mine/counter-mine warfare). Two specific examples of the recent efforts to develop and field UANs in shallow water regions are the Deployable Autonomous Distributed System funded by the Office of Naval Research (ONR) and the Autonomous Oceanographic Sampling Network sponsored by ONR and the National Science Foundation.

The Deployable Autonomous Distributed System (DADS), envisioned to provide undersea surveillance in littoral waters [Rice 2000], is an underwater array of fixed sensor platforms, interconnected by acoustic modems. The network connects the remote sensor platforms to a command center through a portal that relays data received from the acoustic network to the distant command facility across satellite links. Acoustic data is propagated through the network over multi-hop communications paths. The individual hops are configured as half duplex code division multiple access links between discrete modem pairs. Messages are relayed between paired platforms to minimize the transmit power requirements and reduce the impact of temporal, spatial, and frequency spreading of the signal as it propagates through the littoral channel.

The Autonomous Oceanographic Sampling Network (AOSN) is intended to provide a mechanism for gathering data relative to a collection of various oceanographic problems, allowing improved charting, forecasting, measuring, and modeling. [Curtin 1993] Central to the AOSN concept is the deployment of mobile data collection platforms – Autonomous Underwater Vehicles (AUVs). The inclusion of mobile collection platforms allows the sensor network administrators to adapt the sensor field to evolving collection requirements by tasking the AUVs to collect data between the fixed nodes, increasing data fidelity, or to extend the range of the field, both horizontally and vertically, beyond the practical reach of fixed sensor grids.

One major challenge in the UAN area of research is the development of a networking protocol that can cope with the adverse underwater communications environment and still meet all the application requirements. In the remainder of this section, we will first describe the networking model of UANs, focusing on the underwater acoustic communications environment and the application requirements, and then explain why the current UAN networking protocols fall short and a new approach is needed.

1.1 Networking Model of UANs

A typical UAN topology is illustrated in Figure 1. The network consists of fixed and mobile sensor platforms and one or more gateways. The gateway node is equipped with an acoustic modem to interface with the other sensor platforms across the UAN, and a high-speed interface to the external user. The high-speed interface could be either a long distance, over the horizon, high frequency (HF) transceiver, a line-of-sight very-high frequency (VHF) transponder, an ultra-high or super-high frequency (UHF or SHF) satellite transceiver, or simply a wire or fiber tether.

The communications in an underwater acoustic environment must overcome extreme conditions that combine to adversely impact throughput, latency, and capacity. The physical layer considerations include multi-path distortion, signal absorption, frequency-selective fading, and extreme propagation delay. The delay also severely affects the network layer protocol that must provide for efficient routing of traffic through the network.

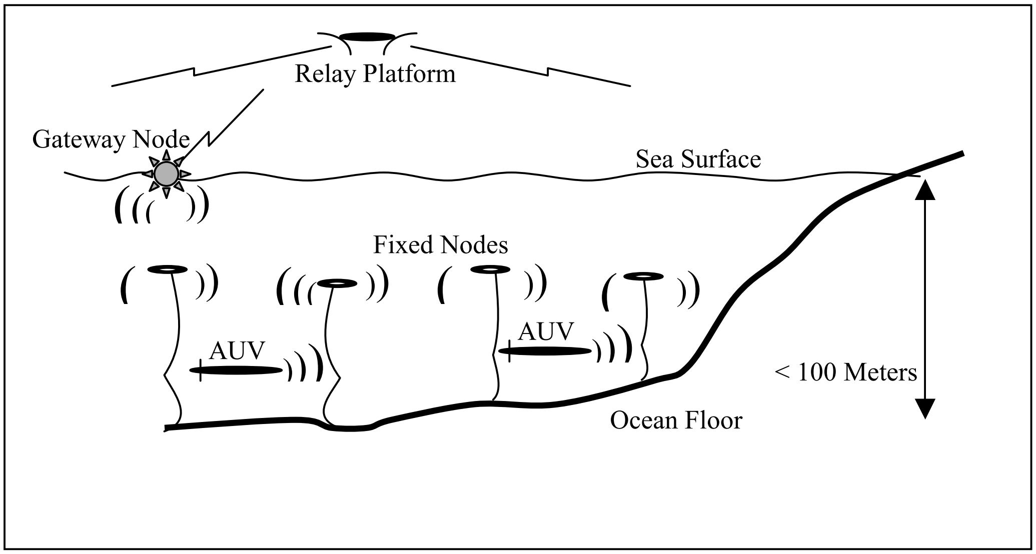


Figure 1. Nominal Underwater Acoustic Network

The data rate within an acoustic network is severely limited by the physical properties of the communication medium, some of which are listed in Table 1. Three key factors affect the data transfer capacity of the network: (1) transmit power which requires a trade-off between node battery or power cell life expectancy and signal propagation range, (2) bandwidth availability which restricts data rate and the number of co-existing channels, and (3) propagation delay which introduces communication latency and possibly large jitter.

Signal Range	10 – 90 Kilometers
Total Bandwidth	8 – 15 Kilohertz
Signal Propagation Delay	.67 sec/km

Table 1. Communication properties of Underwater Acoustic Networks [Sozer, 2000]

Typical acoustic networks support a bit rate of 100 to 1000 bits per second (bps), although Eggen reports a bit rate of 2500 bps over 3 km with a carrier frequency of 20 KHz. [Eggen 2000]. Separately, Sharif reports 16 kbps. [Sharif 2000] Kilfoyle suggests a range rate curve for acoustic networks, where the product of range and data rate for deep water, vertical channel applications is 40km-bps. However, for shallow channels the product, according to experimental results, is closer to 5000 km-bps. [Kilfoyle 2000]

Each of the UAN nodes, both fixed sensor nodes and AUVs, are battery powered. Therefore, transmission power must be managed to preserve battery life. Two issues are of concern here: the average number of retransmissions required to successfully send a packet between the source and destination which requires the routing of the packet between platforms -- a classic network access problem, and the transmit power level -- a physical layer concern which must be considered. Limiting the transmit power level has the effect of reducing the received signal energy per bit, thus reducing the signal to noise ratio. The net reduction in signal strength further limits the number of bits that may be sent per unit of time.

The available bandwidth for an acoustic network typically is not more than 15 KHz. This bandwidth must be shared among all users. Time Division Multiple Access (TDM) and Frequency Division Multiple Access (FDM) methods have been investigated for providing media access to multiple users. These appear less than desirable due to the combined effects of multi-path distortion, large propagation delay and selective fading. Code Division Multiple Access (CDMA), either using frequency hopping (FH-SS) or direct sequence spread spectrum (DSSS) techniques, offer mechanisms for controlling multiple access while overcoming some of the multi-path and fading problems. This effort presupposes the use of CDMA as it offers a method to establish unidirectional links using the spreading codes. However, a means of providing code reuse, similar to frequency reuse in cellular networks, must be included. Limiting the transmit power or allocating the frequency spectrum to separate regions may provide the necessary separation. Either action further reduces network throughput potential.

One of the key factors adversely impacting the achievable throughput is the propagation delay of sound in water. At approximately 1500 meters per second, acoustic signal propagation is more than 130,000 times slower than electromagnetic signal propagation through guided media and 200,000 times slower than through air. Given this difference, a relatively short propagation path in water has the same delay impact and consequent utilization impact as a traditional network link 100,000 to 200,000 times longer. It would be comparable to implementing a double-hop satellite path to connect two UAN nodes that are less than 1-kilometer apart. The propagation delay in a 1-kilometer acoustic channel is the same as that of a 134,000-kilometer wire or fiber optic channel. With demonstrated transmission rates of 5,000 bps over 1 kilometer, and assuming a nominal packet size of 1500 bits, the default maximum transmission unit size for point-to-point links (1492 for IEEE 802.3/802.2 compliance), the ratio of propagation time to transmission time is 2.23. This gives a maximum theoretical utilization of 31%, assuming no overhead. [Stallings 2000] In general, utilization rates are directly proportional to total data transmission time, and inversely proportional to the propagation delay. These relations will be discussed in the Proposed Research section. When bi-directional traffic or multiple access considerations are included the importance of an efficient network protocol that maximizes the time window for data transmission becomes even more pronounced.

1.2 Application Requirements

While many applications may be proposed that require near real-time delivery of mission critical data or delivery of bandwidth limited video or audio information, due to the severe propagation delays and low bit rates, it can be expected that the bulk of data transmitted in UANs will be limited to numeric data and text. it may be feasible to transmit small imagery, in terms of the number of pixels in length and width, using either mono-color images or JPEG compression techniques. Streaming video may be supported, provided the gateway server has sufficient memory capacity to allow buffering of the acoustic signal until the entire video has been received and can be forwarded over the high speed link to the processing site.

Table 2 lists the data types underwater acoustic networks can expect to support. There is a growing need for time-critical command and control information or streaming video data across the acoustic network. The integration of autonomous vehicles may require the vehicle user to communicate with the vehicle and provide near-real time navigation directives. Delays in the delivery of those messages could lead to failures in vehicle responsiveness or vehicle collisions.

Data Type	**Application**
Numeric Data	Sensor readings, position information, AUV speed, etc.
Text Data	AUV tasking commands, auto-

	configuration messages, etc.
Imagery	Low resolution or monochrome. JPEG images
Streaming Data	Video or audio

Table 2. Anticipated data types of UAN applications

1.3 The Need for a New Approach

Given the harsh communications environment and diverse application requirements, development of a network layer protocol for acoustic networks must balance several competing objectives. These include total throughput, as measured in delivered bytes per second; message latency, as measured by the time between its generation and delivery; and node life expectancy. Figure 2 provides a picture of this focus, where it is assumed that a reliable physical interface is provided and the signal is converted to information bits before presentation to the network layer. The network access layer protocol must provide a means of supporting the setup of communication sessions and the routing of messages.

Application
Transport
Network Access
Physical

Figure 2. Network model

The network access protocol typically used for UANs, and specifically used by the SeaWeb demonstrations, an extension of the DADS program, call for the use of a three- or four-way handshake to facilitate the transfer of data between each pair of nodes. [Sozer 2000] This handshake protocol, as depicted in Figure 3, requires additional control traffic for each session exchange. It requires the exchange of a request to send (RTS) and clear to send (CTS) message pair. The RTS is sent at a pre-designated transmit level. The receiving (destination) station returns the target transmit level for data, as determined by the received signal level of the RTS, back to the source in the CTS message. The third handshake is the actual transmission of data, sent at the transmit power level specified in the CTS by the destination. The fourth handshake is an acknowledgement packet that may be combined with other traffic to reduce the amount of overhead.

In the handshake-based protocols each session incurs a delay prior to transmission of first packet of data. This delay is precisely at the point where the user or application is most sensitive to delay! In effect, the use of aforementioned handshake protocols requires at least a three-fold delay for the forwarding of data, not to include any delay while waiting for acknowledgment. This fact is illustrated in Figure 3. In the example, Node A wishes to forward data to Node C. To reach C, A must relay the data through Node B. Prior to forwarding the data to B, Node A must send a RTS packet to B to which B responds with a CTS packet. Finally, A can forward the data packet. Node B then repeats the procedure with Node C. Thus, for each data relay, two propagation delay terms are added to the total transmission time for each data packet. The messages remain in each node's output queue in turn while the media is accessed through the handshake protocol. Thus, the handshake based data exchange incurs a significant penalty in terms of message latency.

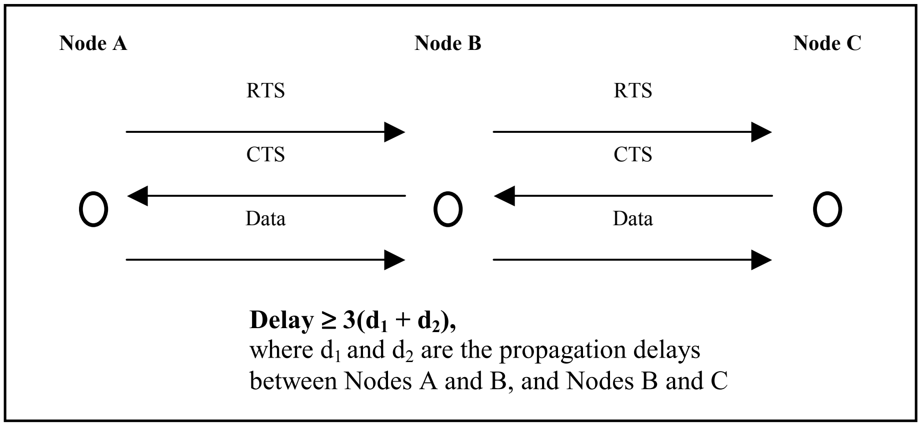


Figure 3. Message delay due to handshake protocol

Moreover, existing UAN networking protocols do not provide a means of controlling the variability in delay that messages experience for a given session. Recalling that the propagation delay for an UAN may be measured in hundredths or even tenths of a second. Thus, network topology changes may occur frequently during a session, resulting in varying transmission path lengths to the gateway. Since propagation delays are amplified by a factor of three for the handshake case, the resulting variance in message delays, referred to as jitter, limits the ability of current networks to support time sequence sensitive data such as video and an AUV's feedback to navigation directives. Therefore, a new approach is needed to address these shortcomings.

2 Problem Statement

We propose development of a protocol that will address the problems associated with existing networking protocols for Underwater Acoustic Networks (UANs). The main objectives are: (1) offer guaranteed and differentiated quality of services on a per session basis, (2) reduce average message latency, (3) increase network throughput for user data, (4) prolong battery life at a given sensor node, and (5) enable the construction of large acoustic networks from composite sub-networks in a hierarchical manner providing scalability over other approaches. Other system considerations, including fault-tolerance and security, will also be addressed.

Our investigation focuses on two novel ideas. The first is reducing message latency by removing as much as possible the dependencies between data plane and control plane communications. The second is using a gateway-centric, proactive approach to achieve robust and efficient topology management and routing despite the harsh physical environment of UANs. Most of the functionality will be added to the gateway so that it may serve as a master node, responsible for management of the acoustic network topology, routing, and allocation of acoustic channel access for member nodes. Consequently, our protocol imposes minimum processing overhead on the non-master nodes.

Initially, our investigation is going to be conducted through computer simulations. Each aspect of our protocol will be modeled and analyzed carefully. At the conclusion of this effort, we plan to implement and demonstrate our protocol on real UAN gateways and sensor platforms as part of a large UAN experimentation. Our goal is to implement the network protocol as part of a technology demonstration in support of the U.S. Navy's on-going SeaWeb program.

3 Solution Approach

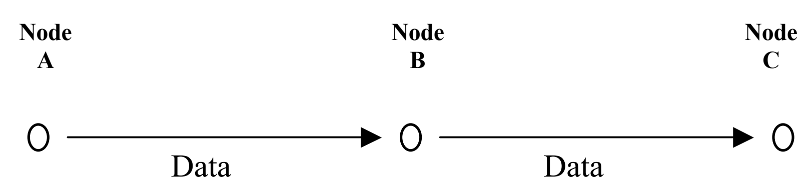
The principal concern of this research is the effects of large propagation delays on message latency and performance guarantees on a per session basis. While other acoustic propagation concerns must be addressed at the physical layer of the protocol stack, the effects of delay on quality of service are most pronounced at the networking access layer, where routing and channel access issues must be resolved.

We have identified three key issues that require investigation in order to build a protocol capable of providing improved message latency and guaranteed performance. They are: topology control, route determination, and media access control. Since it is reasonable to expect that the nodes in an underwater network will be power limited, power expenditure, whether for protocol processing or traffic transmission and reception must be carefully managed. Below we explain the difficulties associated with each of these areas and discuss the significance of their impact on the utility of underwater acoustic networking. We also present our initial thoughts on various means to mitigate these difficulties. A comprehensive analysis of those means is beyond the scope of this report and is left for future work.

3.1 Topology Control

Topology management presupposes the ability to allocate channel resources effectively between network nodes. It involves the gathering of network node information upon which to base effective routing decisions. Network membership will be dynamic in autonomous underwater networks, as the power consumption of each node limits its lifespan. New nodes, fixed or mobile, may be incorporated over the operational life of the network, either to extend the range of the network or enhance its coverage in a specifically targeted region. In each of these cases, the network must be capable of managing the addition or removal of nodes on demand without a system administrator's intervention. This activity is very dependent upon whether the network is managed centrally or in a distributed manner. The choice affects the manner in which network resources are allocated and utilized.

We propose a centralized scheme, as the data capacity of an acoustic network is extremely limited and precise control of the available resources is vital to assuring optimum message latency and network throughput. Specifically, we will investigate the feasibility and efficiency, in terms of user data throughput, of a proactive scheme in which the master node generates a tree topology for the network and updates the parameters (routes, channel codes, transmission power levels, etc.) of each node at fixed time intervals via dedicated control channels. This scheme will allow new nodes to be added dynamically and



Delay ≈ $d_1 + d_2$,

where d_1 and d_2 are the propagation delays between Node A and Node B and between Node B and Node C, respectively.

Figure 4. Message Delay in an Instantaneous Access Network

allow failed or inactive nodes to be removed from the structure promptly, freeing up allocated resources for use by other nodes.

One key advantage of the proposed topology control scheme is that it separates control overhead from data delivery and thus reduces the impact of propagation delays on network responsiveness. By providing a dedicated transmission channel to each node and pre-computing all routes, the proposed protocol provides a node near instantaneous data access to the network. As such, the proposed protocol can deliver messages much faster than the handshake protocol currently in use. This point is illustrated in Figure 4, which shows that for the same scenario as Figure 3, the proposed protocol reduces the message delivery time by approximately 67%.

The proposed topology control scheme can be described as follows. The master node will initiate a network configuration cycle by transmitting a Topology Discovery Message (TDM), which functions as a configuration probe, at a pre-determined transmission level via the dedicated channels, as depicted in Figure 5. The designation of dedicated transmission channels will be accomplished by allocation of the CDMA codes. Most channel assignment concerns will be deferred to a separate section "Code Contention and Media Access Control" below. Included in the probe will be a set of channel code-words selected at random from the entire set of CDMA codes, the ID of the sending node and the transmitted power level. Each node within range of the master node's probe with select one of the codes from the provided set and will send a response to the master node on that channel. The response will include the received signal strength of the received probe, a set of code-words chosen randomly from the entire collection, but not

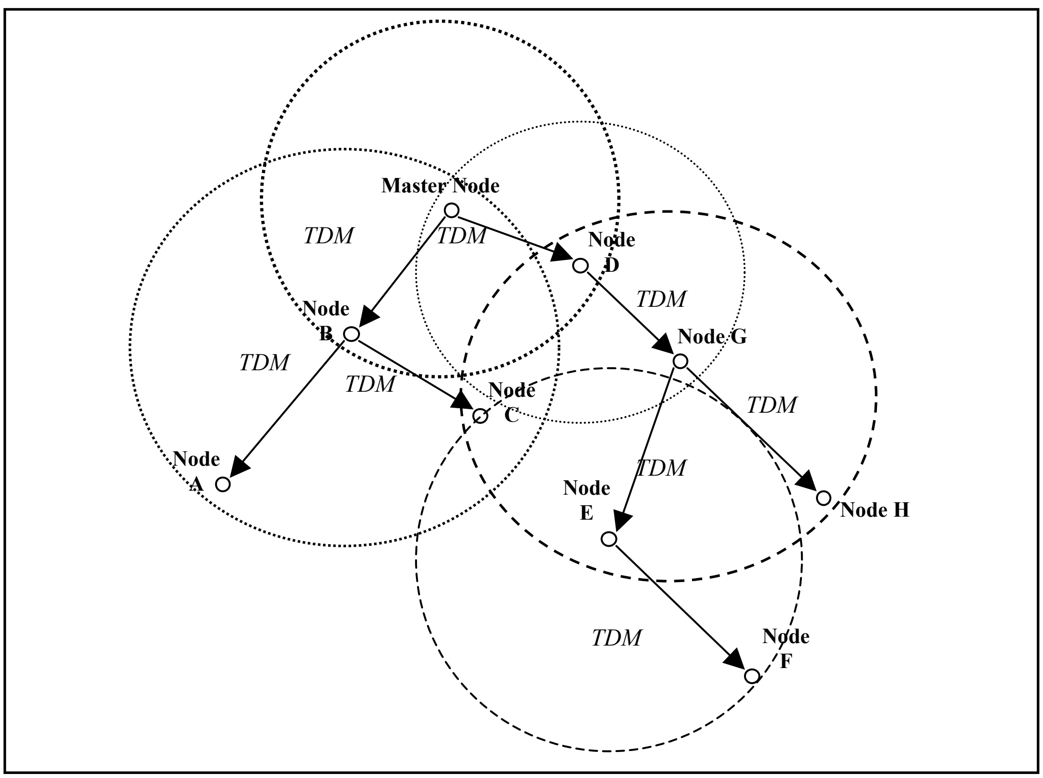


Figure 5. Topology Discovery Message (TDM) Propagation in an underwater acoustic network. Each node forwards the TDM upon receipt. Circles represent the signal propagation radius about a given node.

including any forwarded by the received probe, the respondent's ID appended to the ID list contained in the probe, and the respondent's current power availability. The response will also be transmitted at the lowest power level possible necessary to insure its receipt by the initiator of the received probe, based on the power level contained in the received probe and the received signal level. This reduction in transmit power ensures the minimum power level is used to propagate traffic, limiting the effective range and conserving power reserves. The response, formatted in the same manner as the initial probe, serves two functions. The first is to report back to the probe's source the identity of each node within range of the probe. The second is to facilitate controlled flooding of the probe through the network.

Each node will process the topology probes (responses) it receives and respond accordingly. However, to limit the degree of flooding induced, no node will respond to a probe that contains its ID in the included ID list. This also prevents generation of cycles in the list of contacted nodes.

If no response is received within a timeout period, as determined by the expected propagation range as constrained by the transmitted power level of the outstanding probe, then the node will resend the probe with the power level increased to the pre-determined level of the initiation probe. Should the response time out again, taking into account the increased range of the probe, then the node will assume that it is on the periphery of the network and transmit a topology completion message to the master node, transiting through each of the nodes contained in the ID list of the probe it received. Each node in sequence will append to the topology completion message a list of its immediate neighbors so that upon receipt of all topology completion messages the master node has complete information regarding membership of the network and each node's immediate neighbors. From this information the master node will generate route information for directing traffic within the network.

Periodic topology discovery probes will ensure the master node has current network status information and is able to make effective route determinations. The frequency of probes must be evaluated to ensure the network capacity is not unduly impacted. As the acoustic environment is time variant, the periodicity of topology probes allows the network to adjust to changes in the propagation characteristics of the water channel. Thus, as the signal propagation improves the transmit power levels can be reduced. When propagation deteriorates, transmit levels can be increased. Measurement and reporting of the channel conditions as part of the topology maintenance overhead ensures timely adjustment of power levels, power conservation resulting in maximum node life expectancy, and identification of available codes for reuse, while limiting the proliferation of control traffic. All these trade-offs will be modeled, simulated and addressed.

There are several concerns raised when considering centralized management of a network. These include fault tolerance and scalability. Failure of the master node must not induce overall network collapse. This vulnerability can be reduced by providing sufficient robustness in the master node to reduce its likelihood of failure and by fielding backup nodes to assume network management in the event the master node fails. A fail-over scheme must be devised and implemented which enables the backup nodes to monitor the health of the master node and coordinate assumption of the master role should failure of the master node be detected. This scheme must include recovery or regeneration of all network management data controlled by the master node. All these fault tolerance issues will be investigated.

Scalability addresses the ability of a network protocol to support increasingly larger networks. Hierarchical structures have been applied to large organizations to manage the effort of controlling those organizations. This effort will investigate the feasibility of combining several small networks into a composite network where a master-node manages the flow of traffic across the entire network by coordinating the actions of each of the smaller networks' master nodes. This feature ensures the scalability of the protocol.

Next, an example of the propagation of a topology discovery probe from the master node to the outlying nodes is shown. The example demonstrates the ability to reach all nodes in the sample set with seven transmissions of the probe.

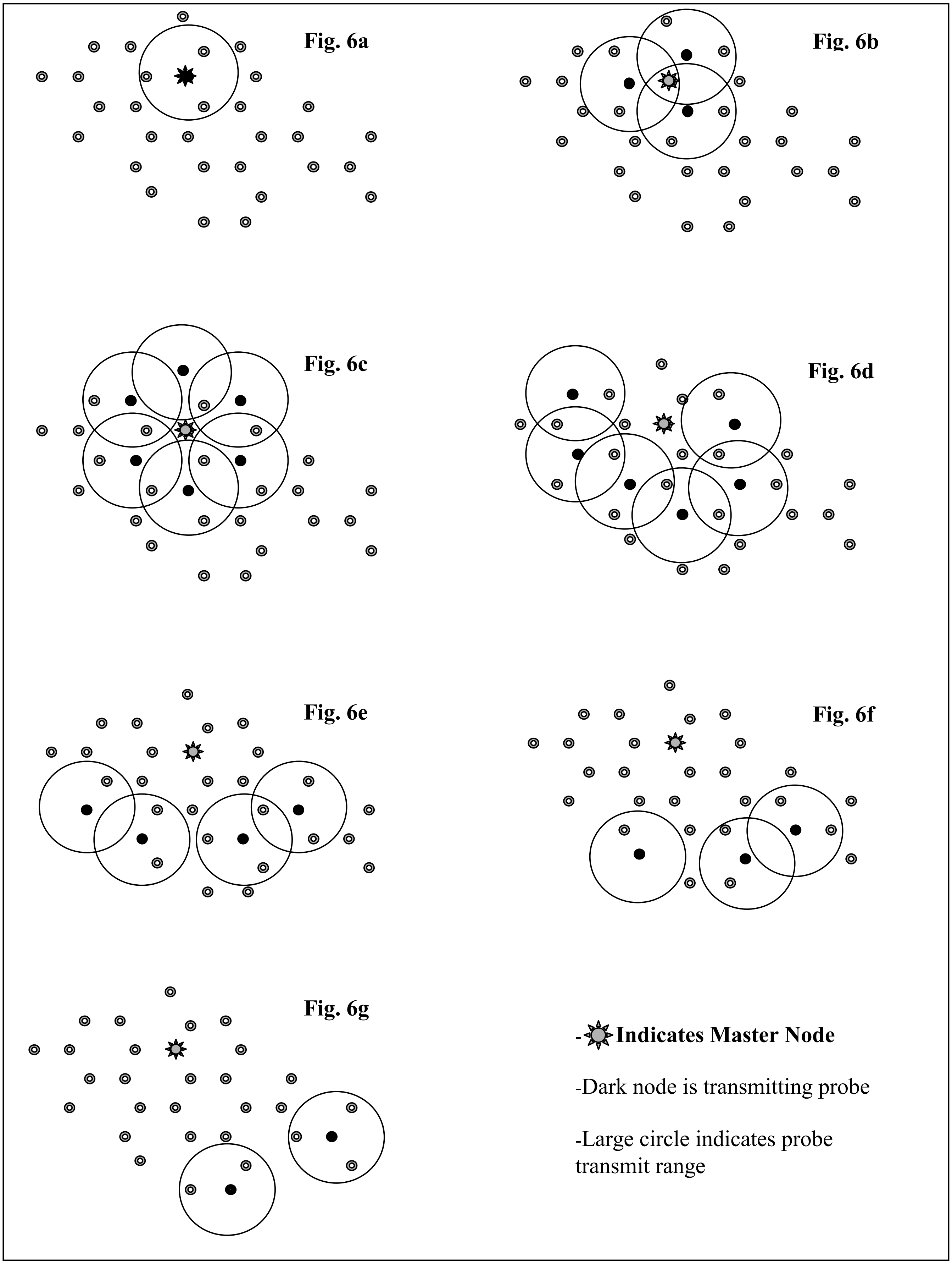


Figure 6. Topology Discovery Probe Dissemination

C.3.2 Routing

The utility of the topology management scheme may be seen in the effectiveness with which it allows nodes to forward data traffic. Since the master node determines all routes through the network and provides next hop information specific to each network node, the nodes are able to forward data without first determining routing information. Further, as the master node has information for all possible routes between node pairs, it is able to select from among multiple routes to balance traffic across the network, further optimizing power consumption at the individual nodes. Centralized routing provides a capability to perform global planning of network resource allocation. This is critical to effectively limiting delay variance for a given application session. Controlling delay variance is an essential aspect of providing both guaranteed and differential qualities of service. Further, by evaluating the battery power availability of all nodes constituting given paths, the master node may route traffic around nodes that are near failure due to low power reserve.

Within the network two general categories of paths exist, paths which terminate at the master node, and paths connecting any two non-master nodes. All paths are considered unidirectional. For the first type of paths the routing information is determined as part of the topology discovery probe/response activity. Contained within a probe received by any node is a list of all nodes between the recipient and the master nodes. This provides a routing for traffic originating at the recipient destined for the master node. Traffic may be forwarded to the master simply by relaying it, in turn, through each of the intermediary nodes in the list. The master node also has complete routing information to each individual node once it receives the topology completion message from outlying, or boundary, nodes.

However, route determination for member-to-member transactions requires the master node select the most appropriate path to be used, based on current available capacity across the path, power reserves along the path, or the number of hops which must be traversed to reach the destination. The paths are determined by extracting the sets of neighbor pairs from the topology completion messages. These pairs then form the links that comprise the complete paths. Before a source may send information to another non-master node it must receive allocation of a path from the master node. This allows the master node to perform load balancing or provide guaranteed qualities of service.

It can be expected that non-master nodes may need to exchange single packet messages. In these cases requiring them to first receive an allocated path from the master node results in excess overhead with respect to the traffic sent. We propose the master node establish an expedient path between each pair of non-master node, as part of the topology management action, to be used by default for all "limited size" messages exchanged between the respective nodes.

These two types of exchanges, either including the master node and one other node, or between two non-master nodes, pose different issues. For the former, the hierarchical structure of the network, where all traffic "funnels" to the master node through "rings" of decreasingly smaller numbers of nodes, holds the potential of inducing bottle necks, either in the nodes closest to the master node or within the master node itself. While these bottlenecks may reduce the flow of traffic to or from the master node they may also result in earlier failure of the choke points due to increased power consumed by forwarding the transit information. The latter traffic may cause increased overhead as the sources request path allocations from the master node, as mentioned in the previous paragraph. Both of these situations require investigation to ensure the devised protocol improves performance of the network over that achieved by non master-node centric protocols.

By generating the set of all paths traversing the network from the topology reports, the master node is able to select the most appropriate paths between any two nodes. When a node fails all paths through that node become unavailable. The master node must inform all other nodes of the failure and provide an alternate path for any traffic destined for the failed paths. The delays which would have been encountered had the master node not collected the neighbor node information during the last topology discovery cycle would have adversely affected the service quality provided to traffic on the failed paths. The path data managed by the master node is critical to per-session performance guarantees.

As asserted above, the utilization rate, albeit a rough indicator of the effectiveness of a networks performance and use of available resources, is affected by the speed of signal propagation, the distance between communicating nodes, transmission bandwidth, and packet size. The speed of propagation is a physical characteristic of the medium and not subject to control. Likewise, the available bandwidth is constrained by the shallow water environment and is further limited by the multiple access requirements of the shared medium. However, the distance between the nodes and the size of the packets are subject to network design consideration. Providing each active node a dedicated, unidirectional channel enables the node to provide a continuous flow of data, provided the node has data to send. This potentially continuous flow maximizes the channel utilization. However, without separation of the control traffic from the application data the near-continuous flow of data is not possible. Careful management of the physical separation between nodes must also be given to allocation of channel codes and node power reserves. These issues are discussed in the next section.

With the establishment of a dedicated transmission channel for each node, the master node can manage the variation in delays that may impair real-time data or streaming video. By establishing route information in advance the delays that would have been imposed in determining an available route when traffic is presented are avoided. This limits the delay experienced by traffic transiting the network to queuing delays and propagation delays. Since the routes are determined ahead of time an entire session the propagation delay for each packet of that session is constant, as the packets traverse the same route. This provides predictability and stability in traffic delays, minimizing both uncertainty with respect to the expected arrival of time sensitive information and jitter. The SeaWeb 99 demonstration used a master node to control routing for a set of pre-configured nodes. This research effort extends the findings of that demonstration by developing a protocol that enables the network to be configured autonomously.

3.3 Code Contention and Media Access Control

CDMA techniques are assumed for providing a set of transmission channels for the network. The use of unique, orthogonal codes forms point-to-point links between neighboring nodes. Each node will be assigned one channel for submitting traffic to the network and must be able to listen on all other channels. The ability to monitor multiple channels requires multiple transducers on each modem. This channel will be allocated as part of the topology discovery and maintenance effort describe above. The number of available code-word allocations, corresponding to “channels,” is a function of the available bandwidth and the number of tones assigned to each code. The amount of transmission power used by a node determines the maximum range the signal will propagate, as limited by the acoustic medium. By limiting the power levels the number of nodes within a given footprint can be managed, thus effectively limiting the number of code-words required by the network. Controlling the transmission range of each node provides two fundamental benefits. The reduced transmission power expenditure optimizes node power reserves and it enables the network to re-use code-words along the same principle as frequency reuse in cellular applications. This idea will be explored. The goal is to determine the optimum transmission range of a node.

While the extreme delay experienced in acoustic networks is only one of the difficulties that must be addressed by the lower level protocols, it is perhaps the most serious for the network layer. Effective management of those delays is vital to providing sustained, predictable service to network users. Delay may be introduced within the nodes, either in the form of message processing or as time spent waiting in queues. Since the propagation delay of the acoustic medium is so large, time spent waiting for access further exaggerates the problem. Establishing a dedicated transmission channel for each node serves to mitigate the access delay problem, however; it is possible for contention to occur during the channel allocation function of topology management as two or more nodes respond to the same topology probe.

Although a node selects a response "channel" randomly from those provided to it in the probe, it is possible for more than one node in receipt of the same probe to select identical codes. The protocol must be able to recover from these collisions. When this occurs the probe source must generate an amended probe to notify the affected nodes of the contention or assign a code directly to each node if the originator can distinguish the nodes whose probe responses collide. Since the probe source will likely have received some responses the amended probe should include them to reduce excessive probe propagation. The affected nodes will need to coordinate the change in channel differentiating codes with their neighboring nodes. This last issue is akin to the "hidden node" problem that occurs when two nodes are within range of a common third node but not within range of each other.

3.4 Security

This section has identified three key areas of difficulty with respect to the network layer protocol of acoustic networks. An additional concern that is common to all three areas is the feasibility of an unauthorized agent attempting to join the network and access information to which he is not privileged or to deny access to the network for others who are authorized. The use of CDMA code-words to establish network links provides a limited access control method in that before a node may attempt to join the network it must have access to the set of code-words that delineate the active channels. To further minimize the risk of unauthorized access or denial of service attacks we propose cryptographically encoding the control traffic associated with topology management and path allocation and distributing the keys to only those nodes which have been authenticated to the master node. Authenticating requesting nodes will make use of certificates issued to the requestor by a third party trusted by both the requestor and the network master node. Upon validation of the requestor's identity, the master node will forward the keys to the requestor that will enable it to participate in the network topology management actions. Further investigation is required to find the authentication solution that has the smallest communication overhead while still ensuring security.

4 Technology Transfer

This effort will directly support the National Science Foundation's goals of advancing the relevance of classroom activities to real world issues and fostering cross discipline collaboration and understanding. Student participation will be incorporated at both the Master's and doctorate levels. Such activity will include both small-scale class projects and more in depth thesis efforts.

The results of this effort will be made available to the research community and the public at large by posting the developed software on a project web site. Distribution of the software will be uncontrolled except by a license agreement to ensue its proper application.

Potential for transfer of findings include support to the AOSN program and integration into the SeaWeb demonstrations. The results may also be applied to other research problems such as migration studies of sea mammals or monitoring of fisheries. Completed research findings may be useful for the initiation of dual use technology proposals.

5 Related Work

Current wireless routing methods (AODV, CBRP, DSR, etc.) have serious drawbacks with respect to their suitability to underwater acoustic networks. [Ramanathan 1996, Broch 1999, Perkins 2000, Boukerche 2000] Two key characteristics bear consideration- when routes are determined and who determines them.

Proactive or pre-computed routing techniques seek to establish routes prior to the generation of traffic requiring them. These typically are based on link state or distance vector algorithms, such as Open Shortest Path First, or similar methods for establishing routes. These methods introduce significant overhead as each node must determine the most appropriate route to every other node in the network. Changes in the topology can introduce a surge of overhead as the network attempts to cope with those changes. However, as traffic is introduced the next hop for each segment is already known at each router. Therefore, no delay is incurred while waiting for the next hop information to be acquired. However, many routes may never be required, as some node pairs may never need to communicate.

When a session is requested between two nodes in a reactive or ad hoc network, the source node in normally floods a route determination message its neighbors, and on through the network until a feasible route is found. This route information is returned to the source and traffic is then forwarded along the provided route. Dynamic Source Routing is one such method. The advantage of reactive routing is that routes will be determined only for nodes needing to communicate with each other. Routes for nodes which do not need to exchange information will not be computed. A critical drawback is that delay is introduced for the first packet of a session for which the required path is not already known. Further, if a route fails additional delay is incurred while an alternate path is found.

For air-propagating networks the delays introduced while determining routing information may not be significant. However, the relative slow propagation speed of sound in water presents a significant barrier when messages must be exchanged to determine routing information before a packet may be sent. Requiring each node to maintain complete or at least partial network topology information can impact the router's performance and induce scalability problems.

To overcome the scalability issue of proactive networks and control the delay variance suffered in reactive networks, the Server and Agent Based Active Network Management (SAAM) Protocol introduces a mechanism for controlling the allocation of network resources by a central server and performing all route decisions at that server. [Xie 1998, Quek 2000, Akkoc 2000, Gibson 2000] The SAAM protocol controls the network as a hierarchy of coordinated routers. Each router reports its status and hosted interfaces to the central server. The server determines all routes through the network based on the reported node status and allocates network resources to applications requesting support. By generating and maintaining the routing paths periodically the protocol has some aspects of proactive routing. However, by periodically probing the network for router status it accomplished much of the adaptability of ad hoc networks. SAAM researchers have also addressed server fault tolerance and security issues. Their initial results show that SAAM is very suitable for managing land-based high-speed integrated service networks with point-to-point links. However, it is still unclear how the SAAM approach can be adapted to underwater acoustic networks. The proposed research will provide definite answers to this question.

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